DEVELOPMENT OF AC-DC CONVERTER INCORPORATING WITH ACTIVE POWER FILTER FOR BATTERY CHARGER APPLICATION

Mohd Hafiz bin Abdullah
Faculty of Electrical Engineering
Universiti Teknologi MARA Malaysia
40450 Shah Alam, Selangor, Malaysia
E-mail: Mohdhafiz6990@gmail.com

***Abstract* – This paper presents a smart AC-DC converter for battery charger application using boost rectification technique for power factor correction (PFC) to compensate the harmonics generated and to achieve a power factor near to unity. In this technique, the system used proportional-integral controller as a medium to reshape the current waveform to sinusoidal and in phase with the supply voltage waveform. The simulation of this circuit was done by using MATLAB simulink software and hardware prototype was built according to this circuit design. The result shows that the current is operating in phase with the voltage, hence improve the power factor and reduce the THD level.**

***Keywords*—AC-DC converter, PI controller, boost rectifier, power factor correction, total harmonics distortion (THD), power factor (PF).**

I. INTRODUCTION

A power converter is normally used in power electronics system as an interface between load and supply. It can be generally classified in term of basics function, namely AC-AC convertion, AC-DC convertion, DC-DC convertion and DC-AC convertion [3].

Most of electrical and electronic appliances in the world today are using DC power supplies inside their equipments, such as computers, televisions, audio sets, battery charger and others [1]. So, the AC supply from main utility must be convert to DC and this converter is known as rectifiers. The rectifiers contribute to low power factor, high total harmonics distortion and low efficiency to the power systems. By referring harmonics standards, IEEE 519 Standard, the THD level must be less than 5% and this would be much important aspect to consider in every design of the appliances.

The AC mains that connected to power supplies is supposed to be cleaned and free from harmonics current in order to ensure good quality and efficient power system to electronics equipment. Usually this harmonics current will produce when non linear load is used. The non linear nature of devices is drawing current waveform that doesn't follow the voltage waveform and producing the harmonics [7]. These harmonics current can cause several problems such as voltage distortion, equipment malfunction, overheating, noise, increase power losses and reduce the capability of the line to provide energy.

Furthermore, low power factor can affect the appliances to absorb the energy more than it should be. Power Factor Correction (PFC) is presented to eliminate the unwanted drawing current. The system that has PFC will save the current usage by only draw to the extent of their uses only. In a simple explanation, PFC chargers require less incoming energy to provide the same output of the non-PFC chargers. The PFC is measured by how efficiency the AC sine wave is used. In a non-PFC charger, the circuitry has a delayed reaction to the alternating current in the incoming sine wave. When PFC is utilized, it will eliminate the delay and allows the circuitry to use the incoming AC more effectively.

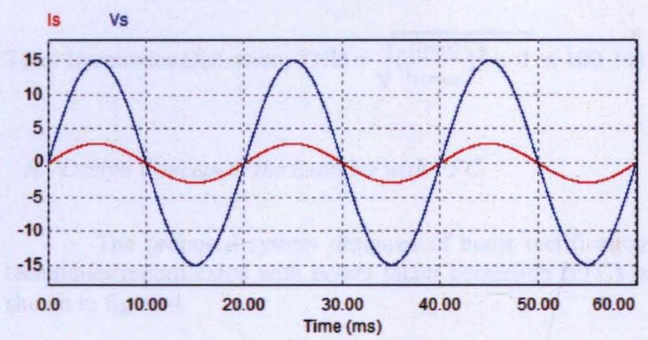

Figure 1: Waveform of related voltage and current

Figure 1 shows that the voltage and current waveform are in phase which is unity power factor. The waveform shown is the best input current that all the appliances especially non-linear load should be. There is no harmonics and have unity power factor.

The objective of this paper was to reduces the harmonics current according to IEEE 519 Standard and to achieve power factor near to unity. By using boost rectification techniques, which is properly controlled by related circuitry, the input current could be shaped to follow the sinusoidal form of the input voltage.

II. METHODOLOGY

A. Analysis of a Basic Rectifier Circuit

A rectifier circuit is a converter of an alternating voltage supply to direct voltage. It is one which links an AC supply to a DC load.

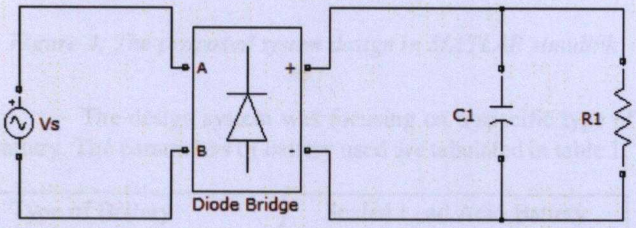

Figure 2: Basic rectifier circuit with capacitor filter

Figure 2 shows the basic configuration of a rectifier circuit. For DC output, the capacitor filter must be design carefully to allow the voltage ripple to allowable range. Battery manufacturers recommend that under normal float conditions, battery ripple RMS (Root Mean Square) voltage must be limited to less than 0.5% of the DC voltage applied to the battery [6].

Ripple Voltage < 0.5% * V_{float}

This ensures that the instantaneous cell voltage will not fall below the open cell voltage or rise above the maximum float charge voltage. It also eliminates the consequential battery heating that would occur from constantly cycling the battery through discharging and recharging states.

The range of voltage ripple can be adjusted by determined the value of capacitor filter. Here is some basic explanation about how the capacitor work and its effect on voltage ripple. When the instantaneous voltage, V_S is higher than the instantaneous capacitor voltage, V_C, the capacitor is then charged from the supply. If the instantaneous supply voltage, Vs falls below the instantaneous capacitor voltage, V_C, the capacitor, C_1 is discharges through the load resistance, R_l [8]. The capacitor voltage, V_C varies between a minimum value $V_{C(min)}$ and maximum value $V_{C(max)}$ as shown in figure 3.

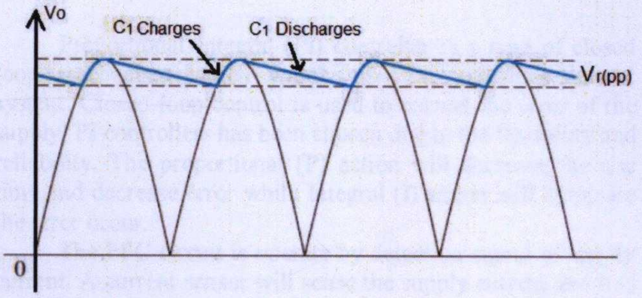

Figure 3: Waveform of full-wave rectifier

The equation of finding the minimum value of capacitance is shown below.

$$C_{cr} = \frac{1}{4fR}\left(1 + \frac{1}{\sqrt{2}RF}\right) \quad (1)$$

$$= \frac{1}{4(50)(150)}\left(1 + \frac{1}{\sqrt{2}\times 0.005}\right)$$

$$= 4747\mu F$$

Since, $C_1 > C_{cr}$

$C_1 = 6800\mu F$

For a basic rectifier circuit (bridge diode followed by a capacitor in parallel with the load) without PFC, the input current would be highly non-linear or high harmonics especially when the capacitor is having large value.

Two factors that provide a quantitative measure of the power quality in electrical system are Power Factor (PF) and Total Harmonics Distortion (THD). The equation below are their formula.

$$\text{Power factor, PF} = \frac{P(real\ power)}{S(apparent\ power)} \quad (3)$$

$$\text{Total Harmonics Distortion, THD} = \sqrt{\left(\frac{I_{(rms)}}{I_{1(rms)}}\right)^2 - 1}\ \text{x}\ 100 \quad (4)$$

B. Design Concept of the Rectifier with PFC

The proposed system designed of boost rectification techniques incorporated with power factor correction (PFC) is shown in figure 4.

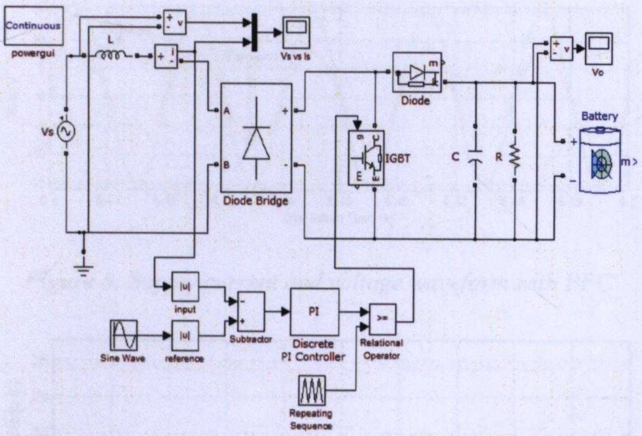

Figure 4: The proposed system design in MATLAB simulink

The design system was focusing on a specific type of battery. The parameters of battery used are tabulated in table 1.

Type of Battery	Sealed Lead Acid Battery
Nominal Voltage	12V
Rated Capacity	1.2 Ah
Initial Current Charging	Less than 2.36A

Table 1: Parameters of Battery

A rectifier with capacitor filter is the capacitive load. This makes the current lead the voltage. To improve the system, inductor would be added across the line for power factor correction [2]. The value of inductor must be larger than a certain value to make the current continuous [8]. The calculation for finding the minimum value of L is shown below.

$$L_{cr} = \frac{V_m}{\omega I_{pk}} \tag{2}$$

Where;

$$V_m = \sqrt{2} \times 15V = 21.213V$$

$$x = \frac{V_{dc}}{V_m} = \frac{15}{21.213} = 0.707$$

$$k = \frac{I_{dc}}{I_{pk}}\left[\sqrt{1-x^2} + x\left(\frac{2}{\pi} - \frac{\pi}{2}\right)\right] = 0.047$$

$$I_{pk} = \frac{I_{dc}}{k} = \frac{2.3}{0.047} = 48.936$$

$$L_{cr} = \frac{21.213}{(2\pi)(50)(48.936)} = 1.380 \text{ mH}$$

Since, $L_l > L_{cr}$;

$L_l = 1.5\text{mH}$

Proportional Integral (PI) controller is a type of closed loop mechanism which widely used in industrial control system. Closed loop control is used to correct the error of the supply. PI controllers has been chosen due to the flexibility and reliability. The proportional (P) action will decrease the rise time and decrease error while Integral (I) action will eliminate the error occur.

The PFC circuit is operate by detection signal of supply current. A current sensor will sense the supply current and it is subtracted from sinusoidal reference to give the required error signal. Then, this signal is send into the current loop PI controller. The PI controller is use to reshape the input current so as to reduce the harmonics. The output of this signal represent the modulating signal for the PWM. The switching frequency of 20kHz is choose as a carrier signal in PWM circuit. It is chosen to be fast so that the supply can track the reference closely. The input current of inductor should be able to track the change of reference current. Thus, the supply current can operate in phase with the supply voltage and achieve the goal of power factor correction.

III. RESULT AND DISCUSSION

The results of the project are divided into two parts which is simulation in MATLAB simulink and laboratory experiments. The AC-DC rectifier was supply with 15V AC voltage source. The proposed system was using proportional gain 16 and integral gain 27 in PI controller. The other parameters are shown in table 2.

Supply voltage	15V
Resistor	150Ω
Capacitor	6800μF
Inductor	1.5mH

Table 2: Parameter of Circuit

a. *Simulation Result in MATLAB simulink*

The results of the simulation using MATLAB simulink are shown in figure 5 through figure 9. In making a better result display, the output of current sensor in attached with gain. The scale used is Vs : Is = 1 : 4.

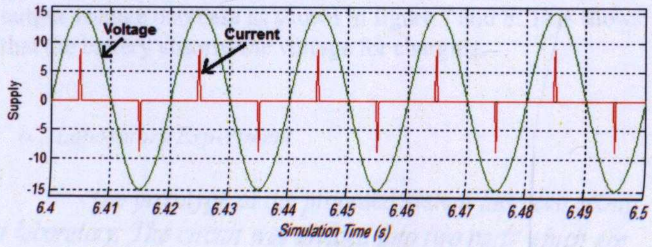

Figure 5: Supply current and voltage waveform without PFC

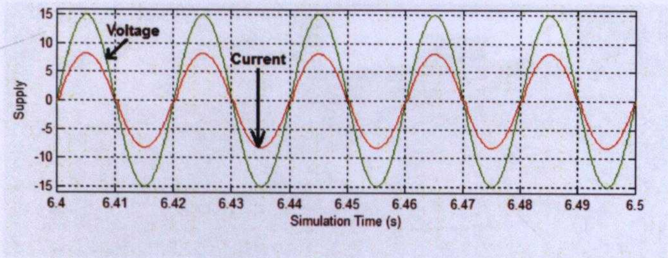

Figure 6: Supply current and voltage waveform with PFC

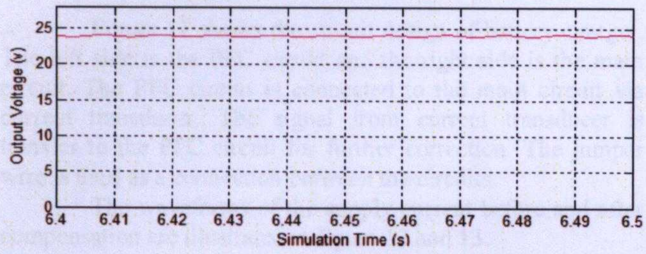

Figure 7: DC output voltage before connected to the battery

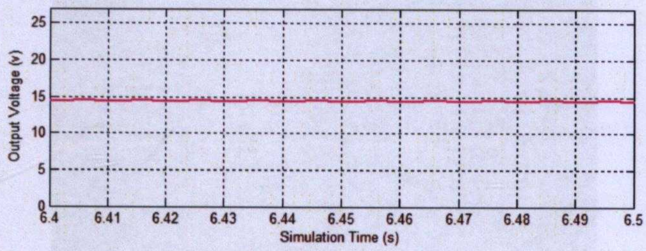

Figure 8: DC output voltage after connected to the battery

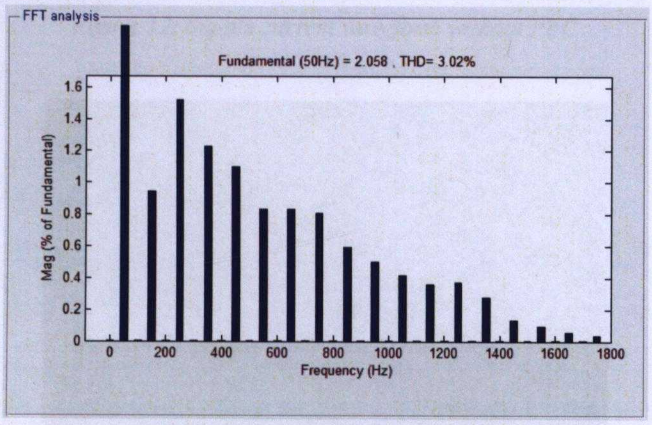

Figure 9: FFT of the supply current after compensation

All the result simulation results is taken when the voltage reach steady state which is about 6.4 second after running. From the figure 6, we can see that the supply current and voltage are in phase, meaning a good achievement of PFC function. The boost rectification technique gives a quite satisfactory for power factor correction. The calculation of the power factor in MATLAB simulink is through the measuring instrument of active power (P) and reactive power (Q).

$$P = 15.20W$$
$$Q = 0.13VAR$$

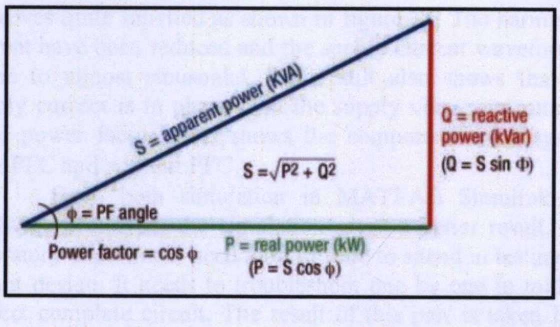

Figure 10: Relationship between Real, Reactive and Apparent power

Figure 10 shows the relationship between real, reactive, and apparent power. From the measuring instrument of P and Q, the value of apparent power (S), can be calculated.

$$S = \sqrt{P^2 + Q^2} \tag{5}$$

$$= \sqrt{15.2^2 + 0.13^2}$$

$$= 15.2006 \text{ VA}$$

By referring to the equation (3), power factor can be calculated as below.

$$\text{Power factor, PF} = \frac{P(real\ power)}{S(apparent\ power)}$$

$$= \frac{15.2000}{15.2006}$$

$$= 0.99996$$

The result indicates that power factor can be maintain up to 0.99996, while the total harmonics distortion (THD) that obtained from simulation is 3.02%, which that satisfy the IEEE 519 Standard below 5%.

When the circuit is connected to the battery, the output voltage decrease as shown in figure 7 and 8. This shows that the battery absorbs the voltage for charging.

b. Laboratory Experiment

The prototype of the proposed system has been set-up in laboratory. The circuit was divided into two parts which are main circuit and PFC circuit. The PFC circuit design used is an analog type.

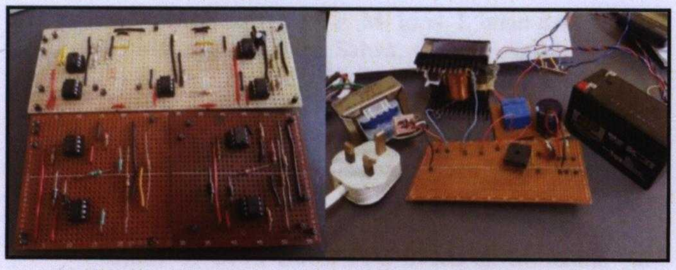

Figure 11: The hardware of circuit design

Figure 11 shows the circuit design of battery charger. The left side is the PFC circuit and the right side is the main circuit. The PFC circuit is connected to the main circuit via current transducer. The signal from current transducer is transfer to the PFC circuit for further correction. The jumper wire is used as a connection between the circuits.

The waveforms of the supply current before and after compensation are illustrated in figure 12 and 13.

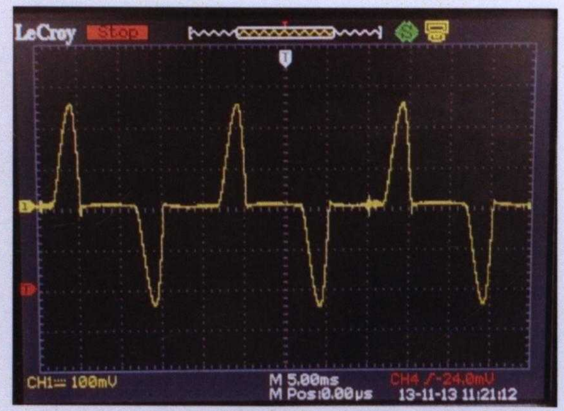

Figure 12: Supply current waveform without PFC

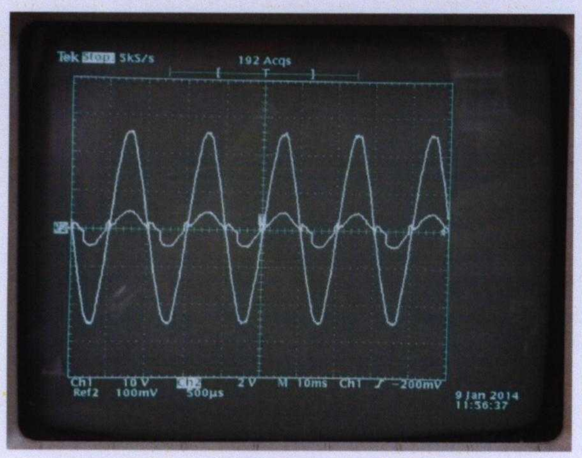

Figure 13: Supply current waveform with PFC

The waveform shown in figure 12 is a supply current which is taken from a basic rectifier circuit. When a rectifier with only capacitive filtering, the current drawn is discontinuous and short duration current spikes emerges. The harmonics current is high and may damage the appliances. When PFC is connected to the main circuit, the current supply improves quite satisfied as shown in figure 13. The harmonics current have been reduced and the supply current waveform is shape to almost sinusoidal. The result also shows that the supply current is in phase with the supply voltage meaning a good power factor. This shows the comparison of a system with PFC and without PFC.

From both simulation in MATLAB Simulink and hardware prototype, the simulation gives a better result. The laboratory experiment need a lot of time to spend in testing the circuit design. It needs to troubleshoot one by one to make a perfect complete circuit. The result of this part is taken from the best simulation with the time limit given. It is not a perfect similar result to the simulation in MATLAB.

The harmonics reduce can save the equipment malfunction and improving power factor gives the appliances absorb less energy.

IV. CONCLUSION

Non-linear load can produce high harmonics and low power factor. By using boost rectification techniques, this two problems can be solved and in addition, reducing energy consumption. Improving power factor can actually reduce losses and furthermore, reducing the cost of electricity. The harmonics current that cause several problems such as voltage distortion, equipment malfunction, and overheating can also be eliminate. The THD level without PFC is 392.96% and the THD level with PFC is 3.02%, which comply the IEEE 519 Standard.

For future work, it is recommended to use digital implementation as a PFC circuit. The PFC circuits that use analog require more time to analyze and tested compared to a digital implementation. Usually, PIC device is used as a medium to do PFC works in a digital circuit. Although it is required programming, but it is easy to implement the control algorithms. The programming is also flexible for modification to meet specific requirement.

V. REFERENCES

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